Mon. Not. R. Astron. Soc. **260**, 681–685 (1993)

Cygnus X–3 light-curve model in the TeV energy region

I. V. Moskalenko,[1,2] S. Karakula[1] and W. Tkaczyk[1]

[1] *Institute of Physics, University of Lodz, ul. Pomorska 149/153, 90–236 Lodz, Poland*

[2] *Institute of Nuclear Physics, Moscow State University, 119 899 Moscow, Russia*

Accepted 1992 August 3. Received 1992 July 13; in original form 1992 February 5

ABSTRACT

We consider a close binary system containing a compact object and suggest that very high-energy (VHE) γ-rays are produced near this object. In such a system the VHE γ-rays have to interact with soft photons around the companion star by $\gamma\gamma \rightarrow ee$ reactions. These soft photons have a radial distribution, so the VHE γ-rays will reach the observer when their source lies between the companion star and the observer, because the reaction is impossible if the angle between the momenta of soft photon and γ-quantum is small. In this model the VHE γ-ray light curve has a sharp maximum at the orbital phase region 0.2–0.8 for orbits with various orientations and eccentricities. Our calculations show that for the orbital parameters of Cygnus X–3 the light-curve maximum occurs at phase ≈ 0.6, which is in agreement with recent experimental data.

Key words: binaries: eclipsing – stars: individual: Cygnus X–3 – gamma-rays: theory.

1 INTRODUCTION

During the last decade many papers have discussed the VHE γ-radiation from various Galactic sources. A considerable proportion of such sources are binary systems like Cygnus X–3, Hercules X–1 and Vela X–1, which contain a compact object (most probably a neutron star).

Unusual properties of the X-ray binary system Cygnus X–3 (4.8-h period) have been the subject of many recent papers (e.g. see review papers of Bonnet-Bidaud & Chardin 1988; Protheroe 1987). All existing models connect the generation of the VHE/UHE γ-radiation with π^0 production by the beam of particles which are accelerated by the compact object, at the companion star atmosphere (e.g. Vestrand & Eichler 1982; Kazanas & Ellison 1986; Berezinsky 1987) or at accreting matter near the object (Protheroe & Stanev 1987; Hillas 1984). The observed 4.8-h modulation is probably orbital in nature, but orbital models, which assume that VHE γ-rays are generated at the companion atmosphere, have a lot of difficulties. It is easy to explain in these models the γ-pulses at phases ≈ 0.2 and/or ≈ 0.8, but the origin of the maximum at phase ≈ 0.6, such as was recently observed for the Cygnus X–3 system (Bonnet-Bidaud & Chardin 1988; Protheroe 1987), remains incomprehensible.

In a previous paper (Moskalenko, Karakula & Tkaczyk 1991), we have considered the model of a close binary system, which contains a compact object and an ordinary hot companion star. The main assumption of our model is that VHE γ-rays are produced near the compact object (e.g. via π^0 production as has been discussed in papers by Protheroe & Stanev 1987 and Hillas 1984). In such a system the VHE γ-rays produced have to interact with soft photons around the companion star by $\gamma\gamma \rightarrow ee$ reactions. These soft photons have a radial distribution, so the VHE γ-rays will reach the observer when the VHE γ-ray source lies between the companion star and the observer (because, if the angle between the momenta of soft photon and γ-quantum is small or zero, the reaction is impossible). In this model the VHE γ-ray light curve has a sharp maximum at the orbital phase region 0.2–0.8 for orbits with various orientations and eccentricities. The model is applied for the explanation of the observed properties of the Cygnus X–3 system.

Some possibilities of investigating point VHE γ-ray sources with the *Gamma-Ray Observatory* (*GRO*) are discussed.

2 DESCRIPTION OF THE MODEL

The main assumption of our model (Moskalenko et al. 1991) is that VHE γ-rays are produced near the compact object; their modulation results from their absorption on the radial photon field of the companion star.

The angular distribution of soft photons from the companion star at the point A (Fig. 1a) is approximated by the radial dependence in the δ-function form, and we choose the Z-axis in the observer's direction:

$$N(\varepsilon, \cos\theta, d) = n(\varepsilon)\,\frac{R_S^2\,\delta(\cos\theta - \cos\alpha)}{2d^2}, \tag{1}$$

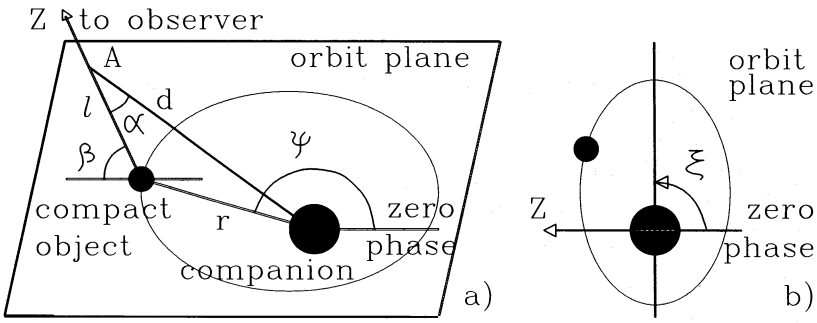

Figure 1. The geometry of a close binary system.

where ε is the energy of the soft photon, θ is the angle between the momentum of the soft photon and the Z-axis, $n(\varepsilon)$ is the number density of soft photons with energy ε at the companion star surface, the angle α is shown in Fig. 1(a), R_S is the effective companion star radius (the distance from the companion star centre, where we normalize the soft photon density to the Planck density), and d is the distance from the point A to the companion star. The constant 1/2 in the formula (1) is needed, because only half the number of photons have momenta outwards from the companion's surface.

Using approximation (1) we can find the inverse mean free path-length of γ-quanta at the point A, which pass from the compact object to the observer:

$$\lambda^{-1}(E_\gamma, \alpha, d)=\frac{4R_S^2}{E_\gamma^2 d^2}\int_{m_e c^2}^{\infty} \mathrm{d}\varepsilon_0\, \sigma_{\gamma\gamma}(\varepsilon_0)\, \varepsilon_0^3 \times \int_{\varepsilon_0^2/E_\gamma}^{\infty} \mathrm{d}\varepsilon\, \frac{n(\varepsilon)}{\varepsilon^2}\, \delta\left(1-\frac{2\varepsilon_0^2}{\varepsilon E_\gamma}-\cos\alpha\right), \tag{2}$$

where m_e is the electron rest mass, $\sigma_{\gamma\gamma}$ is the cross-section of the $\gamma\gamma \rightarrow$ ee reaction, and ε_0 is the energy of a γ-quantum in the centre-of-mass system of two colliding photons. In the formula (2) we have used the relation $\cos\theta = 1-2\varepsilon_0^2/(\varepsilon E_\gamma)$.

The VHE γ-ray flux at the observer position is

$$I_{\mathrm{obs}}(E_\gamma)=I_0(E_\gamma)\exp[-K(E_\gamma)], \tag{3}$$

where $I_0(E_\gamma)$ is the flux from the compact object and the attenuation coefficient $K(E_\gamma)$ is given by the formula

$$K(E_\gamma)=\int_0^{\infty}\frac{\mathrm{d}\ell}{\lambda(E_\gamma, \alpha, d)}. \tag{4}$$

In this formula the integration over ℓ takes place along the line of sight (Z-axis) from the compact object to the observer. In complete form the equation for the attenuation coefficient (4) is

$$K(E_\gamma)=2\,\frac{R_S^2}{E_\gamma}\int_0^{\infty}\frac{\mathrm{d}\ell}{\ell^2+r^2-2\ell r\sin i\cos\psi} \times\int_{m_e c^2}^{\infty}\mathrm{d}\varepsilon_0\,\sigma_{\gamma\gamma}(\varepsilon_0)\,\varepsilon_0\, n(\chi), \tag{5}$$

where

$$\chi=\frac{2\varepsilon_0^2}{E_\gamma}\left[1-\frac{\ell-r\sin i\cos\psi}{(\ell^2+r^2-2\ell r\sin i\cos\psi)^{1/2}}\right]^{-1},$$

and r is the distance from the compact object to the companion star, i is the inclination angle of the orbit [$i=90°-\beta$; β is the angle between the line of sight and the orbital plane as shown in Fig. 1(a)]; ψ is the angular position of the compact object (the position $\psi=0°$ corresponds to the case when the compact object lies behind the companion star).

For binary systems (like Cygnus X-3), zero phase corresponds to the minimum of the X-ray light curve. In the general case of the phase calculation, it is necessary to take into account the unevenness of the orbital motion. When the angular position of the compact object is ψ, the orbital phase is

$$\varphi=\frac{1}{2\pi ab}\int_0^{\psi}\mathrm{d}\psi'\, r^2(\psi'), \tag{6}$$

where a is the semimajor axis of the orbit, $b=a(1-e)^{1/2}$ is the semiminor, and e is the eccentricity parameter. The distance from the companion star to the compact object is

$$r(\psi)=\frac{a(1-e^2)}{1-e\cos(\psi-\xi)}, \tag{7}$$

where ξ is the angle between the main axis of the elliptical orbit and the $\psi=0$ direction (see Fig. 1b).

The calculated phase position of the γ-radiation maximum versus the eccentricity parameter is shown in Fig. 2 for some values of the orbital disposition parameter ξ and for inclination angles i not far from 90°. The γ-ray maximum corresponds to the position of the compact object in front of the companion star. It is seen that the VHE γ-ray light curve has a sharp maximum in the phase range 0.2–0.8 for elliptical orbits with eccentricity parameters in the range 0–0.6. It is necessary to mention that the largest or smallest phase of the γ-pulse occurs when the orbital disposition angle ξ is 90° or 270° (i.e. when the angle between the main axis of the orbit and the line of sight is 90°).

The attenuation coefficient (5) has been calculated for the blackbody soft photon distribution. The value $\frac{1}{2}K(E_\gamma)\,r/(kT)^3/R_S^2$ (which is independent of r and R_S) is plotted in Fig. 3 as a function of $\sin i\cos\psi$ for some values

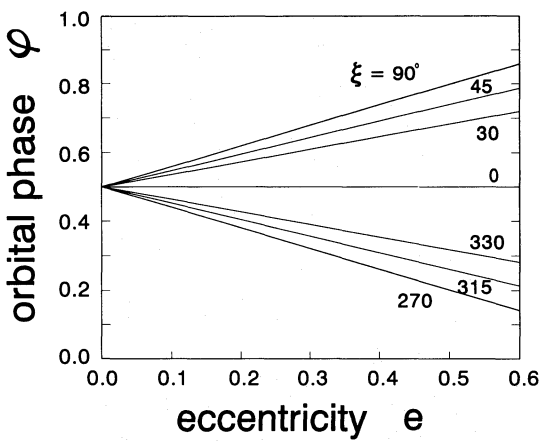

Figure 2. The phase of maximum γ-radiation from the binary system against the eccentricity parameter for some values of orbit orientation angle ξ.

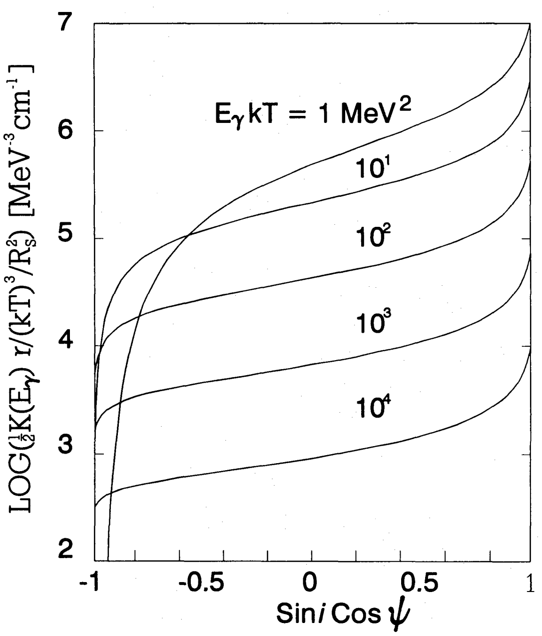

Figure 3. The calculated attenuation coefficient for $\gamma\gamma$-interactions (5) against ($\sin i \cos \psi$) (defined in Fig. 1), for selected values of γ-quanta energy E_γ and temperature of photon field kT.

of the product $E_\gamma kT$. It is seen in Fig. 3 that the value of the attenuation coefficient strongly decreases when the energy of the γ-rays E_γ increases. Moreover, there is a strong dependence on the temperature of the soft photons and the radius of the companion star. We note that the attenuation coefficient $K(E_\gamma)=0$ (no absorption) for $\sin i \cos \psi = -1$, when the observer is in the orbital plane ($i=90°$) and the compact object is between the companion and the observer ($\psi = 180°$). Using Fig. 3 one can estimate the value of the attenuation coefficient for the wide range of temperatures of blackbody radiation kT, energies of γ-quanta E_γ and orbital parameters.

We note that the model can be applied to an arbitrarily close γ-ray binary system, but the soft photon distribution has an important influence on the calculated light curve. Our calculations have been made for blackbody soft photon spectra. For other forms of photon energy spectra the maximum will be at the same phase, but the shape of the light curve will change. The presence of a gas cloud will also change the light curve.

3 CYGNUS X-3 SYSTEM

Cygnus X-3 is a close X-ray binary system in which the X-ray emission is modulated by a 4.8-h period, which is very stable and is normally assumed to be the orbital period. A definite confirmation of the lengthening of the period came from an updated ephemeris in the period 1972–82. The best value of the period derivative $\dot{P}=(1.18 \pm 0.14)\times 10^{-9}$ was obtained by van der Klis and Bonnet-Bidaud (see Bonnet-Bidaud & Chardin 1988). The inverse characteristic time $\dot{P}/P \cong 1.6\times 10^{-6}$ yr^{-1} is typical of the orbital period changes observed in X-ray binaries. The stability of the orbital parameters of the Cygnus X-3 system should be of the order of the characteristic time $P/\dot{P} \cong 10^6$ yr. The distance between the components is estimated to be a few times 10^{11} cm. The object has not been seen at optical wavelengths, due in part to its location in the Galactic plane at a distance of at least 10 kpc from the Sun. Cygnus X-3 has been seen at several other wavelengths: radio, infrared, and VHE and UHE γ-rays (Bonnet-Bidaud & Chardin 1988). No new results of VHE observations of this source have been published recently. The information on the orbital phase of the γ-ray emission at TeV and PeV energies reported before 1987 was summarized by Protheroe (1987). While the early observations (pre-1980) indicate VHE γ-emission at phases $\varphi \approx 0.1$–0.2 and $\varphi \approx 0.7$–0.8, all the later observations in this energy range are clustered around $\varphi \approx 0.6$–0.7. The approximate agreement in phase of emission in all the most recent reported observations is very striking and may provide evidence that VHE/UHE γ-rays are emitted by Cygnus X-3.

At the present time there are many models of the Cygnus X-3 system. Almost all of the existing models connect the generation of the VHE/UHE γ-radiation with π^0 production by the beam of particles which are accelerated by the compact object, at the companion star atmosphere (e.g. see Vestrand & Eichler 1982; Stepanian 1982; Kazanas & Ellison 1986; Berezinsky 1987) or at accreting matter near the object (Protheroe & Stanev 1987; Hillas 1984). The observed 4.8-h modulation is most probably orbital in nature, but the orbital models which assumed VHE γ-ray generation at the companion atmosphere have a lot of difficulties. It is easy to explain in these models the γ-pulses at phases ≈ 0.2 and/or ≈ 0.8, but the origin of the maximum at phase ≈ 0.6, as was recently observed for the Cygnus X-3 system (Bonnet-Bidaud & Chardin 1988; Protheroe 1987), remains incomprehensible. The phase $\varphi \approx 0.6$ corresponds to the position of the compact object in front of the companion, i.e. between the companion and the observer.

There are many papers in which authors have estimated orbital parameters of Cygnus X-3. The determination of these is a very complex problem, because the physical conditions in the system are not known accurately, optical observations are impossible and such orbital parameters are derived from interpretations of X-ray observations. Therefore the orbital parameters are model-dependent and have

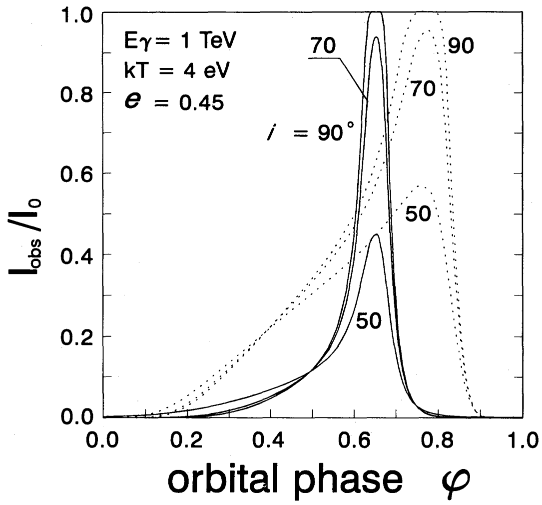

Figure 4. The light curve of the Cygnus X–3 system, calculated for γ-ray energy $E_\gamma = 1$ TeV, eccentricity $e = 0.45$, temperature of photon field $kT = 4$ eV and for different values of inclination angle i. The solid line corresponds to the orbital orientation angle $\xi = 30°$, the dotted line to $\xi = 90°$.

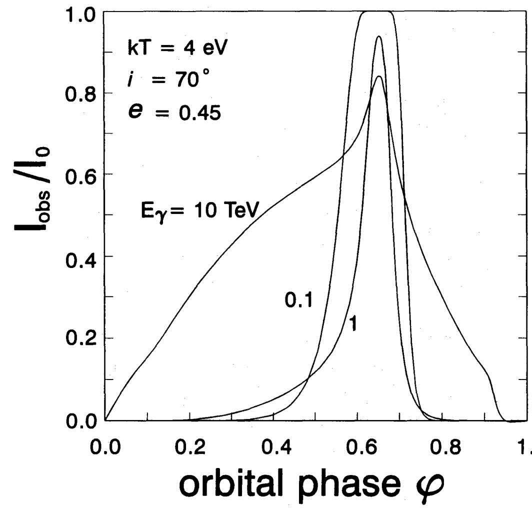

Figure 5. The light curves for the inclination angle $i = 70°$, the orbit orientation angle $\xi = 30°$ and some values of γ-ray energies. Other parameters are the same as in Fig. 4.

large uncertainties. Authors (Ghosh et al. 1981; Giler 1989; Willingale et al. 1985) give various values of the parameters: the eccentricity e is in the range 0.5–0.6 and the inclination angle of the orbit is $i \approx 45°$–$60°$.

We have used our model (Moskalenko et al. 1991) to explain the VHE γ-ray light curve of Cygnus X–3. In Fig. 4 the calculated phase dependence of the 1-TeV γ-ray flux from Cygnus X–3 is shown (formula (3), $I_0 = 1$). The following values of parameters have been taken: eccentricity $e = 0.45$, effective companion star radius $R_S = 10^{11}$ cm, semi-major axis of the orbit $a = 2 \times 10^{11}$ cm, temperature of black-body photon field $kT = 4$ eV (we note that it is the effective temperature of the star, which can be greater than the proper temperature due to X-ray heating by the compact object radiation). The curves are given for the inclination angles $i = 50°$, 70° and 90°, and for the orbital orientation angles $\xi = 30°$ (solid line) and $\xi = 90°$ (dotted line). It is seen that for $\xi = 90°$ and various values of inclination angles the maximum occurs at the phase $\varphi \approx 0.8$. The position of the maximum changes to $\varphi \approx 0.6$ when the orbital orientation angle decreases to $\xi = 30°$. The sharpest maximum is seen when the inclination angle i is 90°, because only for $i = 90°$ is the absorption of VHE γ-rays neglected when $\psi = 180°$ (the compact object located in front of companion star). As the inclination angle decreases, the angle between the momenta of γ-quanta and soft photons increases. So the height of the light-curve maximum decreases due to the increasing possibility of $\gamma\gamma \rightarrow$ ee reactions.

In Fig. 5 the light curves for γ-ray energies $E_\gamma = 0.1$, 1 and 10 TeV are shown ($I_0 = 1$). The curves are given for the inclination angle $i = 70°$ and for the orbital orientation angle $\xi = 30°$; other parameters are the same as in Fig. 4. It is seen that the maximum of the light curve occurs at the same phase for various energies, but the form of the light curves is different. This effect is the result of the energy dependence of the attenuation coefficient. The maximum absorption occurs at the energy near the threshold of pair production $\gamma\gamma \rightarrow$ ee, so the value of the attenuation coefficient decreases with increasing γ-quanta energy as is seen in Fig. 3.

There are some consequences of our model for the Cygnus X–3 system.

(i) The transition of the VHE γ-pulse from phase ≈ 0.8 to phase ≈ 0.6, observed at the beginning of the 1980s (Protheroe 1987), may be connected with the precession of the elliptical orbit of the compact object (as shown in Fig. 4). The period of the precession is estimated as ≈ 60 yr.

(ii) The eccentricity of the orbit e in this case must be greater than or equal to ≈ 0.4 (see Fig. 2), which is in agreement with other calculations (Ghosh et al. 1981; Giler 1989).

(iii) The position of the γ-ray pulse in our model should be around the X-ray maximum position (but not necessarily coincident).

(iv) The peak at phase ≈ 0.2, observed by several groups (Protheroe 1987), is impossible to understand in our model, because the X-ray maximum occurs between phases 0.6 and 0.8 (Willingale et al. 1985). Therefore this peak may be the result of other mechanisms.

(v) The absence of significant VHE γ-emission may now be connected with increasing activity of the companion star, so the VHE γ-radiation is fully absorbed.

(vi) The absorption of VHE γ-radiation (by the $\gamma\gamma \rightarrow$ ee process) could give the increase of the high-energy (HE) γ-radiation (GeV energy range) from the source. This increase is the result of the electromagnetic cascade process, which originates from the primary VHE γ-quanta. Such a cascade also takes place when the phase of the compact object differs from the phase of VHE γ-ray maximum, so the shape of the HE γ-ray light curve will differ strongly from that of the X-ray and VHE γ-ray light curves (two maxima and/or changing phase of maximum are possible in the HE region). However, for accurate calculations of the spectrum of the cascade photons, information about the spectrum of the soft photons from the object in the optical and ultraviolet is needed.

4 DISCUSSION AND CONCLUSION

We present an explanation of the Cygnus X–3 light curve in the TeV energy region. In our model, VHE γ-rays are produced near the compact object. The γ-ray flux is modulated due to $\gamma\gamma \rightarrow ee$ reactions on soft photons around the companion star. This model well describes the observed phenomena of the Cygnus X–3 system. In comparison with existing models (Vestrand & Eichler 1982; Hillas 1984; Kazanas & Ellison 1986; Berezinsky 1987), the present model has some advantages. One of them is that these models connect the VHE γ-ray generation with particle interactions at the companion atmosphere; in this case the VHE γ-ray flux can be observed only in the orbital plane. On the other hand, from X-ray data authors have determined orbital parameters of the system and the inclination angle of the orbit is estimated as $i \approx 45°–60°$. It is the insoluable problem for above-mentioned models to explain the VHE γ-ray maximum at phase ≈ 0.6 and to take into account the fact that the inclination angle is far from 90°. In our model this problem is solved naturally and modulation of the light curve will be observed even far from the orbital plane.

In conclusion we would like to mention the new opportunities provided by the wide energy range γ-ray observatory *GRO* (launched in 1991 April) for understanding of the origin of VHE γ-rays from point sources. Until now, the investigation of such objects has been possible at only some wavelengths: radio, infrared, optical (impossible for the Cygnus X–3 system), X-rays and soft γ-rays, and the VHE/UHE γ-ray region. The vast energy range from ≈ 10 MeV to TeV remains unexplored or is researched accidentally. On the other hand, the most interesting phenomena take place at very high energies. There are some open questions now, e.g.

(i) what is the process of particle acceleration up to $\sim 10^{17}$ eV at point sources?

(ii) what is the mechanism of energy transformation from particles to VHE/UHE γ-rays?

(iii) what is the cause of the VHE/UHE γ-ray light-curve modulation?

The MeV–TeV region is, therefore, very important as the transitional one from soft γ-rays to VHE γ-radiation, and from well-known γ-ray generation processes to obscure ones. For example, for the Cygnus X–3 system the observed phenomena at wavelengths from radio to X-rays are quite clear, but the VHE/UHE ground-based observations remain incomprehensible. We hope that the *GRO* data (EGRET instrument) will help to create a realistic model of this interesting object as well as of other sources (Her X–1, Vela X–1 etc.). It is the simultaneous *GRO* and ground-based observations that will permit us to check predictions of existing models of VHE/UHE γ-emission.

ACKNOWLEDGMENTS

One of the authors (IVM) is very grateful to Professor N. I. Shakura and his coworkers for helpful discussions; he also thanks the Institute of Physics, University of Lodz (Poland) for hospitality. This work was supported in part by the American Astronomical Society and by the Polish Ministry of Education.

REFERENCES

Berezinsky V. S., 1987, Proc. 20th Int. Cosmic Ray Conf., Vol. 9, p. 39
Bonnet-Bidaud J. M., Chardin G., 1988, Phys. Rep., 170, 325
Giler M., 1989, in Stepanian A. A. et al., eds, Proc. Int. Workshop on Very High Energy Gamma Ray Astronomy. Crimea, p. 91
Ghosh P., Elsner R. F., Weisskopf M. C., Sutherland P. G., 1981, ApJ, 251, 230
Hillas A. M., 1984, Nat, 312, 50
Kazanas D., Ellison D. C., 1986, Nat, 319, 380
Moskalenko I. V., Karakula S., Tkaczyk W., 1991, Proc. 22nd Int. Cosmic Ray Conf., OG 4.8.1
Protheroe R. J., 1987, Proc. 20th Int. Cosmic Ray Conf., Vol. 8, p. 21
Protheroe R. J., Stanev T., 1987, Proc. 20th Int. Cosmic Ray Conf., Vol 1, p. 254
Stepanian A. A., 1982, Ap&SS, 84, 347
Vestrand W. T., Eichler D., 1982, ApJ, 261, 251
Willingale R., King A. R., Pounds K. A., 1985, MNRAS, 215, 295